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ESTIMATION OF SOIL MOISTURE WITH RADAR REMOTE SENSING

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ABSTRACT

The radar response to soil moisture content was investigated using a truck-mounted 1-18 GHz (30-1.67 cm wavelength, respectively) Active Microwave Spectrometer (MAS) system. The sensitivity to soil moisture content and the accuracy with which it could be estimated were evaluated for both bare and vegetation-covered fields. Bare field experiments were conducted to determine the optimum radar parameters (frequency, angle of incidence range and polarization configuration) for minimizing the response to surface roughness while retaining strong sensitivity to moisture content. In the vegetation-covered case, the effects of crop type, crop height and row direction relative to the radar look direct were evaluated.

1. INTRODUCTION

The ability to monitor soil moisture variations from a space platform can be considerably useful in a variety of hydrological, agricultural and meteorological applications including crop yield prediction, flood forecasting, runoff prediction for assessing watershed yield and planning and reservoir management. One of the key requirements of the majority of the above applications is timeliness; the success of crop yield models depends on the availability of soil moisture information during critical periods in the growth cycle, forecasting floods requires knowledge of the spatial and depth distribution of soil moisture content particularly before, during and after heavy rainfall activities or rapid snow melt, and similar conditions are imposed by other water resources applications. With regard to timeliness, radar has two major advantages over optical and thermal infrared sensors: a) radar is nearly weather independent and b) radar is time-of-day independent since it provides its own source of (known) transmitted energy. Moreover, radar can provide spatial resolutions from spacecraft altitudes compatible with the needs of water resources applications.

Due to the large difference between the magnitude of the dielectric constant of dry soil and that of water in the microwave part of the spectrum, it has long been postulated that radar should be very responsive to soil moisture content. The first quantitative airborne confirmation of such a behavior was made with a 13.3 GHz NASA/JSC scatterometer which was flown in June, 1970 over an agricultural test site near Garden City, Kansas [1]. During the flight, several of the fields observed by the scatterometer were undergoing irrigation. In each case, the scatterometer output indicated a sharp change as the scatterometer flew between the sections under irrigation and the sections not yet wetted.

In general, radar backscatter from terrain is a function of the terrain geometrical and electrical (dielectric) properties. For a vegetation covered surface, the backscatter includes contributions by the vegetation and the underlying soil. The relative effects of roughness and moisture content on the return and the relative contribution by the vegetation compared to the contribution by the soil and the effect of attenuation by the vegetation, all these

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factors are strongly influenced by the choice of the radar parameters: a) frequency (or wavelength), b) angle of incidence (relative to nadir) and c) polarization. An intensive program was initiated at the University of Kansas in 1971 to determine the optimum radar parameters for sensing soil moisture content of bare and vegetated terrain. This paper represents a review of the present status of the program.

2. SCATTERING COEFFICIENT

The backscatter power received by a radar viewing a cell of area A in the direction θ (relative to nadir) is given by:

$$P_r = \left(\frac{P_t G_t G_r \lambda^2 A}{(4\pi)^3 R^4} \right) \sigma°$$

where,

P_t	= transmitted power
G_t and G_r	= transmit and receive antenna gain, respectively
λ	= signal wavelength
R	= range to the cell A
$\sigma°$	= scattering coefficient, m^2/m^2

P_t, G_t, G_r and λ are usually known, while A and R are calculated from the radar signal waveform parameters (such as pulse width) and the processing algorithms used by the system. Thus, $\sigma°$ is the only parameter relating the terrain backscatter characterisitcs to the observed received power. Because $\sigma°$ usually exhibits a wide dynamic range as a function of angle of incidence, it is usually expressed in decibel (dB) units.

3. SOIL MOISTURE RESPONSE

The Univeristy of Kansas Microwave Active Spectrometer (MAS) was used to acquire radar backscatter data from several crop types over the growing seasons of 1972-1976. In general, it was observed that the backscattering coefficient expressed in dB, $\sigma°$(dB), varies approximately linearly with soil moisture content m, expressed in g/cm^3. As an initial evaluation of the masking effects of the vegetation as a function of microwave frequency and angle of incidence, the radar sensitivity to soil moisture content $S = d\sigma°(dB)/dm$ (which is the slope of the linear regression line between $\sigma°$(dB) and m) was calculated using data acquired from a variety of crop types including corn, milo, wheat, alfalfa, and soybeans for a wide range of growth conditions. Figure 1 presents S as a function of frequency between 4 and 18 GHz at several angles of incidence (relative to nadir). The decrease in S with frequency is attributed to the increase in attenuation by the vegetation. The decrease in S with angle of incidence is attributed in part to the increase in vegetation biomass along the path of the signal to the soil surface and back up to the radar receiver and in part to the decrease in sensitivity to soil moisture of the soil backscattered component itself, as will be shown later for the bare soil case. The behavior depicted in Figure 1 led us to investigate in more detail the radar response to moisture at frequencies below 8 GHz and angles of incidence between nadir and 30°.

3.1 BARE SOIL

At a given angle of incidence, microwave frequency and polarization configuration, $\sigma°$ of bare soil varies with surface roughness, moisture content, and to a lesser extent, soil type. If surface roughness and soil type remain unchanged, $\sigma°$ *generally increases exponentially with soil moisture content.*

$$\sigma_s° = A\ e^{Bm} \tag{1}$$

where A and B are constants for a given λ, θ and polarization configuration Expressed in dB, Equation (1) takes the form:

$$\sigma_s°\ (dB) = Sm + A' \tag{2}$$

where S = 4.34 B and A' = 10 log A. Thus, $\sigma_s°$(dB) varies linearly with soil moisture content (g/cm^3); Figure 2 illustrates this type of dependence for a relatively smooth field with a RMS height of 1.1 cm. Due to the spatial variability of the soil moisture content [2], associated with the soil moisture values of the points shown in Figure 2 is a standard deviation approximately 0.06 g/cm^3 [3]. A statistical.analysis performed to evaluate the effect of this uncertainty in the value of the "ground-truth" parameter (m) on the correlation coefficient between $\sigma_s°$(dB) and m indicates that if the radar response behaves exactly as given by Equation (1), the correlation coefficient would be 0.92 [3]. Hence, the observed correlation coefficient of 0.9 is considered very high when the optimum is 0.92.

In addition to its response to moisture content, $\sigma_s°$ can also exhibit large variations due to surface roughness as illustrated in Figure 3 [3]; shown are $\sigma_s°$(dB) angular responses of five fields with approximately the same moisture content but considerably different surface roughness configurations, as measured at 1.1 GHz (L-band), 4.25 GHz (C-band) and 7.25 GHz (X-band). The parameter used to describe surface roughness is RMS height. The five fields covered a range of roughness from 1.1 cm RMS height (approximately 2.5 cm peak-to-peak variation) to 4.1 cm RMS height (12 cm peak-to-peak variation). Figure 3 provides three important pieces of information:

a) The variation due to surface roughness decreases with frequency; at $\theta = 30°$, for example, the spread in the value of $\sigma_s°$(dB) between the smoothest and roughest fields is about 22 dB at 1.1 GHz, 11 dB at 4.25 GHz and 8 dB at 7.25 GHz.

b) At each frequency, a narrow range of θ exists over which the variation due to surface roughness is small. This range is centered around 7° at 1.1 GHz, 10° at 4.25 GHz and 15° at 7.25 GHz.

c) For a given surface roughness, $\sigma_s°$(dB) exhibits a sharper decay with angle of incidence as the frequency is lowered. Thus, an error in surface slope would result in a larger error in the estimate of moisture content at 1 GHz, for example, compared to 4 GHz [3].

The radar response to soil moisture and surface roughness of bare fields was investigated in 1974 at a test site in Texas [4] and again in 1975 in Kansas [3]. A major difference between the two experiments was soil texture; the soil observed in 1974 contained 49 percent clay in contrast to 17 percent clay in the 1975 soil. The objective of the experiments was to specify sensor parameters at which $\sigma_s°$(dB) is both highly correlated to soil moisture content *and independent of surface roughness. Hence, the correlation coefficient* between $\sigma_s°$(dB) and m and associated sensitivity were calculated (with all fields included) at each angle/frequency/polarization configuration for the 1974, 1975 and combined 1974/1975 data sets. The results, a sample of which is shown in Figure 4, indicate that:

a) In each of the three cases, the same frequency/angle combination provided the highest correlation, namely 4.25 GHz/10° (the actual frequencies used in 1974 and 1975 were somewhat different; in each case, however, one frequency was used in the 4-5 GHz band -- 4.75 GHz in 1974 and 4.25 GHz in 1975 -- and that was the frequency chosen as optimum over the 1-8 GHz band on the basis of correlation with moisture content).

b) Among the three linear polarization combinations, HH was slightly better than HV and VV in terms of sensitivity to soil moisture.

c) The sensitivity S decreases with θ which suggests that it would be more desirable to operate at angles as close to nadir as possible, while retaining independence of roughness.

d) The sensitivity S increases with frequency, particularly between 1 GHz and 5 GHz.

Figure 5 depicts the 1974 and 1975 $\sigma_S°$(dB) response to soil moisture at the optimum radar parameters with all surface roughness configurations included in the analysis. The combined 1974 and 1975 data sets provide a correlation coefficient of 0.83. Although the value of the correlation coefficient is statistically very significant (especially when compared to an optimum possible of 0.92), the slopes of the regression lines corresponding to the 1974 and 1975 data sets are different. In a study of the microwave emission from soils as a function of moisture content, Schmugge et al. [5] observed different sensitivities to soil moisture for different soil types. By converting moisture content to percent of field capacity m_{FC}, they were able to incorporate the effect of soil type in the brightness temperature response to moisture content. A similar approach was used herein as shown in Figure 6. Conversion of moisture content to percent of field capacity does not provide any substantial improvement in the magnitude of the correlation coefficient, but does provide almost identical regression lines. This observation suggests that the radar dependence on soil texture can be removed by expressing moisture content in units of percent of field capacity which incorporates the textural constituency of the soil. From a user's point of view, percent of field capacity is a better input to crop yield and hydrologic models than volumetric moisture content since it eliminates the need to know soil type.

The accuracy with which a radar system can estimate moisture content was evaluated by conducting a classification test. The total moisture range was divided into n intervals, with an approximately equal number of points per interval, and then a linear Bayesian classifier was applied to the data. The classification test was run for values of n between 2 and 7 at each of several frequency/angle combinations. For each value of n, 4.25 GHz/10° provided the highest probability of correct classification. Figure 7 shows the results of the classification analysis at 4.25 GHz. The solid curve represents the probability of correct classification using the mean value of the in-situ measured soil moisture content while the dashed curve represents the classification probability with the spatial variability of soil moisture accounted for. That is, the moisture content was allowed to take any value within $\pm$ 1 standard deviation around the mean. The results are indeed very encouraging; the n = μ case provides a probability of correct classification of 83 percent which is far superior to the current capabilities of any of the conventional meteorological methods as well as to the capabilities of optical and thermal infrared sensors, even when unhampered by cloud cover.

3.2 VEGETATION-COVERED SOIL

If the vegetation and soil backscatter components are assumed to add incoherently, the backscattering coefficient of the canopy (vegetation + soil combination) can be expressed as:

$$\sigma_c^\circ = \sigma_v^\circ + \tau\sigma_s^\circ \tag{3}$$

$$= \sigma_v^\circ = \tau A e^{Bm} \tag{4}$$

where σ_v° is the vegetation scattering coefficient and τ is the two way power transmission coefficient of the vegetation canopy. Unlike the bare soil case, conversion of σ_c° to dB scale does not yield a linear response with m. Comparison of bare soil and vegetation-covered σ° responses to m indicates that σ_v° becomes very small in comparison to the second term in Equation (4) for $m \gtrsim 0.20$ g/cm^3. Hence, as a first order evaluation of the σ_c° response to m, linear regression analyses were conducted involving σ_c°(dB) and m for several crops combined as well as for each crop on an individual basis. The results of the linear regression analyses are summarized in Table 1.

TABLE 1. *LINEAR CORRELATION COEFFICIENT BETWEEN* σ_c° *AND MOISTURE* CONTENT IN THE TOP 1 cm OF THE SOIL, $\theta = 10°$, POLARIZATION = HH.

COVER	1.5 GHz	4.25 GHz	7.25 GHz
Bare Soil	0.69	0.86	0.77
Wheat	0.81	0.80	0.64
Corn	0.85	0.72	0.69
Soybeans	0.90	0.87	0.81
Milo	0.90	0.88	0.86
Corn, Soybeans and Milo	0.49	0.65	0.51
Corn, Soybeans Milo & Wheat	0.51	0.55	0.48

Although it is noted that the 1.5 GHz data provide slightly better correlations than the 4.25 GHz data for single-crop observations, the effects of row orientation relative to the radar look direction can cause substantial reduction in the accuracy of the soil moisture estimate at 1.5 GHz, whereas the 4.25 GHz and 7.25 GHz responses are practically unaffected [3]. The data used for generating the results given in Table 1 included only measurements acquired with the radar look direction within ± 45° of pointing parallel to the rows. Figure 8a presents the correlation coefficient between σ_c° of soybeans and m as a function of angle at three frequencies for data acquired with the radar look direction approximately (within ± 45°) parallel to the rows. For comparison, Figure 8b presents the correlation coefficient based on all the data acquired from soybeans (including some with the radar look direction perpendicular to the row direction). Over the 0° to 20° angular range, the correlation coefficients at 4.25 GHz and 7.25 GHz are approximately the same in both cases (figure 8a and 8b), but at 1.5 GHz, the correlation coefficient shows a fast decrease with angle due to the row orientation effect. This effect is not attributed to the vegetation cover, it is attributed to the row spacing period used in planting row crops (typically 96 cm for corn, milo and soybeans) relative to the radar wavelength. At 1.5 GHz the wavelength is 20 cm which is much closer to the 96 cm spatial wavelength of the soil row pattern than the 7 cm wavelength corresponding to 4.25 GHz. Hence, the same conclusion arrived at for the bare soil case applies also for the vegetation-covered case, namely that the optimum radar parameters for soil moisture determination are: frequency in the 4-5 GHz range, 7°-17° angle of incidence range and HH polarization.

4. CONCLUSIONS

In addition to its inherent cloud-independence and time-of-day independence qualities, radar can provide soil moisture information for both bare and vegetation-covered fields provided its system parameters are properly chosen. Moreover, its performance as a soil moisture mapper can be significantly enhanced if auxiliary information on crop type is made available by an independent sensor such as MSS scanners (under clear sky conditions) or an imaging radar operating in the 8-18 GHz band at angles of incidence higher than 40° [6].

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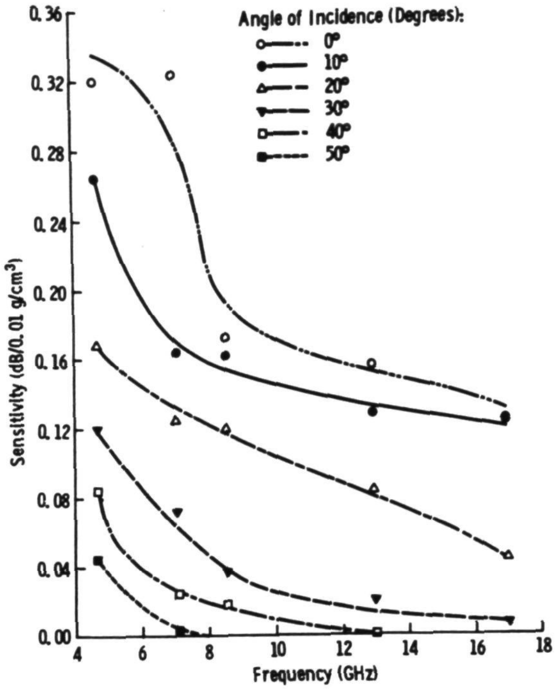


Figure 1. Radar sensitivity to soil moisture content of vegetated fields (corn, milo, soybeans and alfalfa) as a function of microwave frequency.

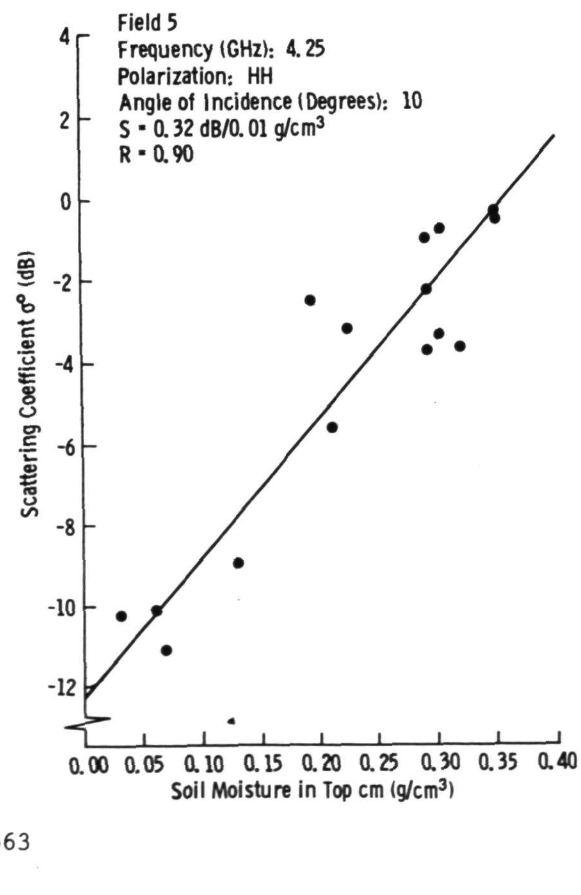
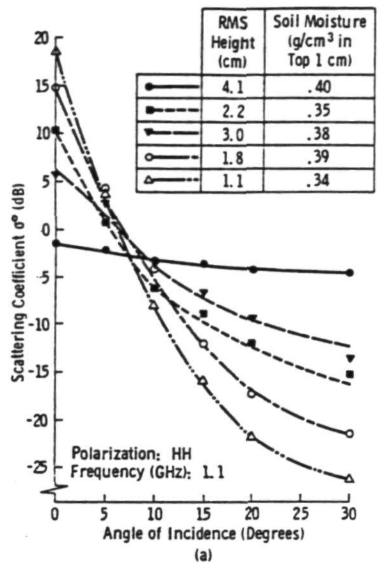
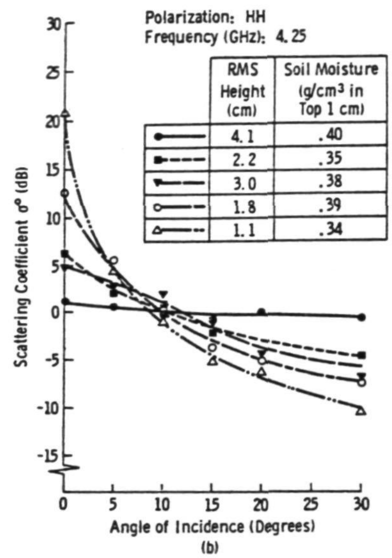


Figure 2. Scattering coefficient of a smooth bare soil field as a function of moisture content.





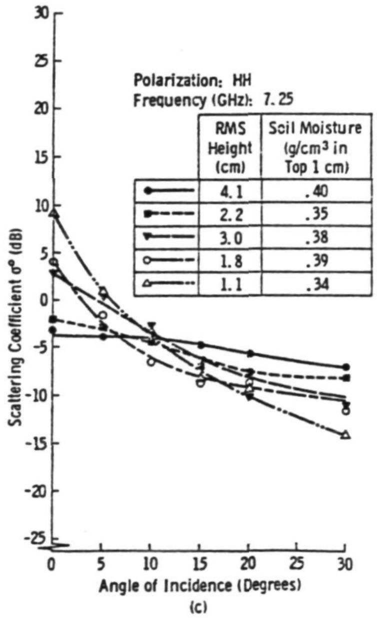


Figure 3. Angular response of scattering coefficient for the five fields for high levels of moisture content at (a) L-Band (1.1 GHz), (b) C-Band (4.25 GHz), and (c) X-Band (7.25 GHz). 1975 soil moisture experiment.

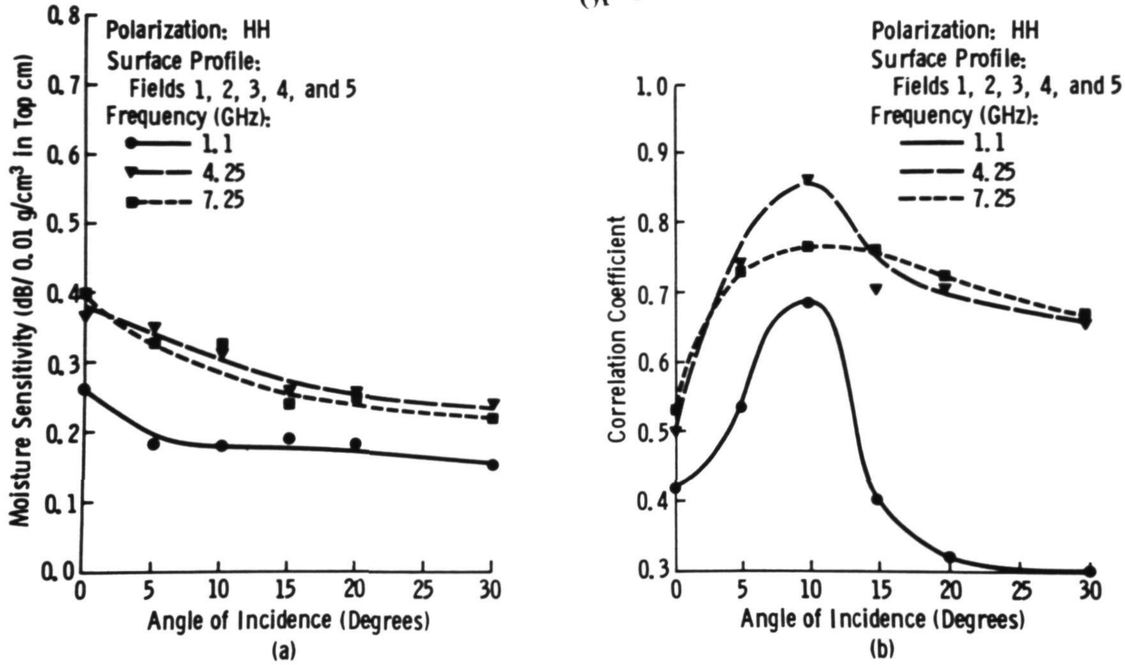


Figure 4 (a) Moisture sensitivity and (b) correlation coefficient plotted as a function of angle of incidence for all five surface roughnesses combined for 1975 data.

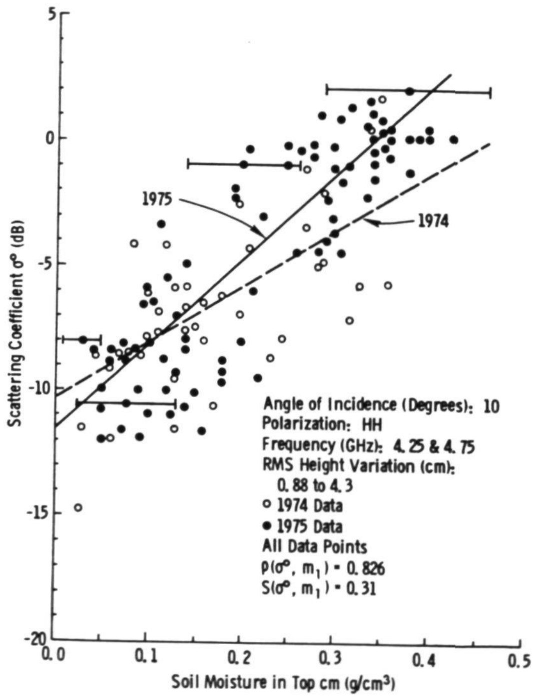


Figure 5. Backscattering coefficient as a function of volumetric moisture content in the top 1 cm of the soil. The indicated correlation coefficient ρ and sensitivity S are for the combined 1974 and 1975 data sets.

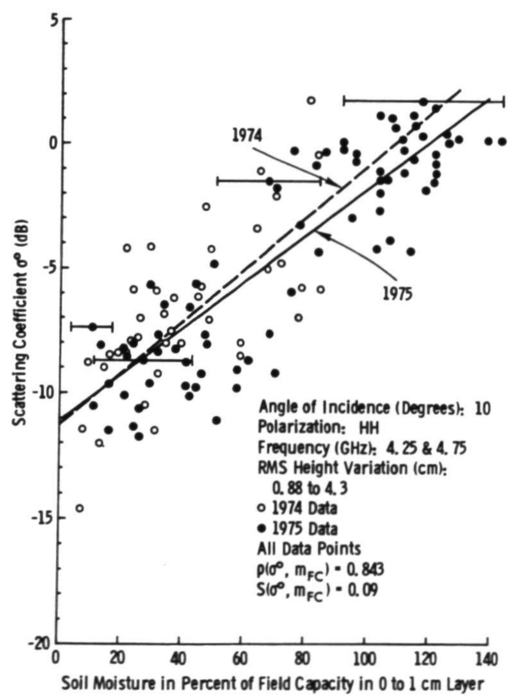


Figure 6. Backscattering coefficient as a function of percent of field capacity in the top 1 cm of the soil. The indicated correlation coefficient ρ and sensitivity S are for the combined 1974 and 1975 data sets. Same as Figure 5.

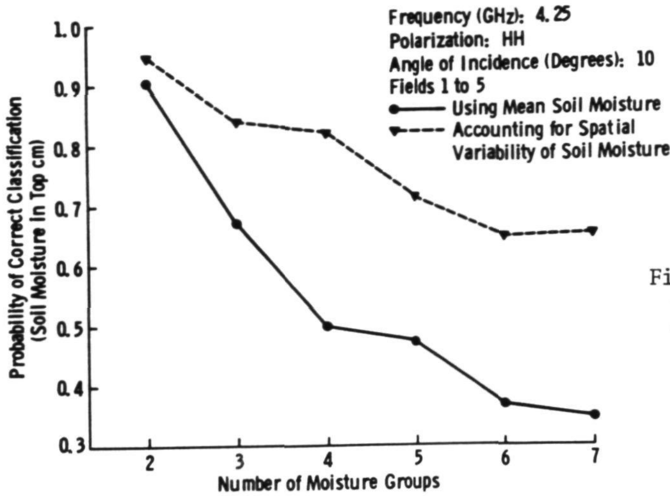
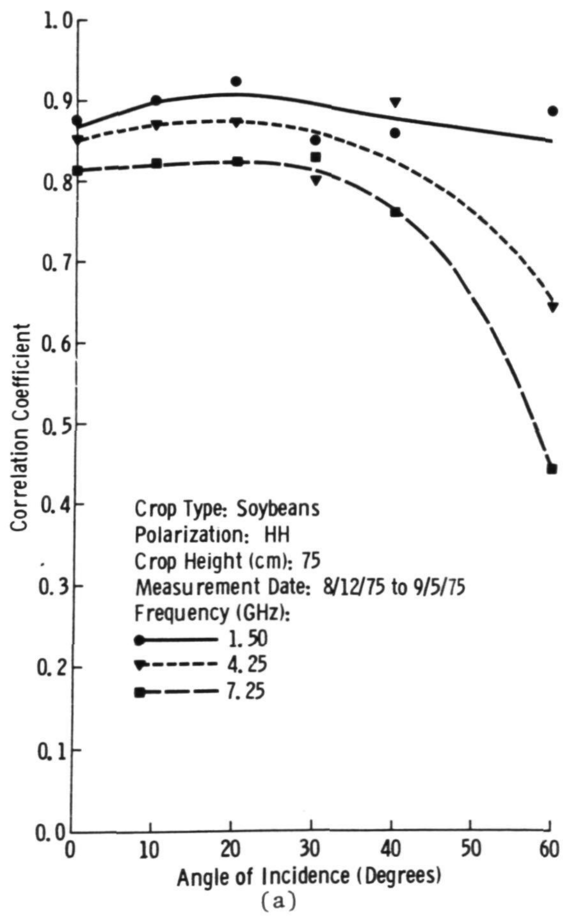


Figure 7. The probability of correctly classifying soil moisture plotted as a function of moisture groups.



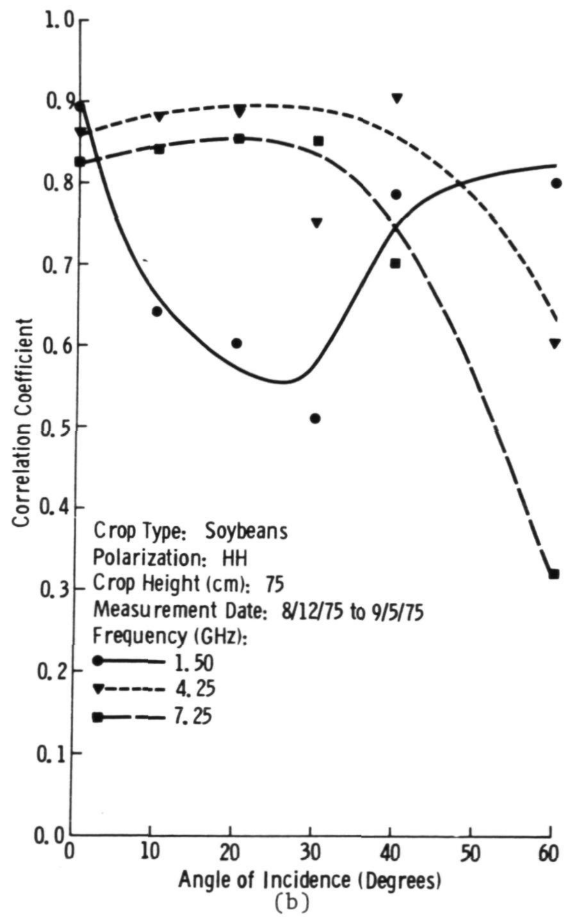


Figure 8. Correlation coefficient between backscattering coefficient and soil moisture for fields planted with soybeans at three microwave frequencies with (a) data limited to radar look direction within ± 45° of looking parallel to the rows and (b) data in all look directions included.